METHOD AND APPARATUS FOR OBTAINING IRRADIATION INTENSITY

OF A LASER BEAM,

AND APPARATUS FOR IRRADIATING THE LASER BEAM

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a method and an apparatus for obtaining irradiation intensity of a laser beam, and an apparatus for irradiating the laser beam.

2. Description of Related Art

Conventionally, an apparatus which irradiates a laser beam is used in a variety of fields for medical treatment and processing. For example, in the field of ophthalmology, there is known a laser irradiation apparatus which changes a corneal curvature by ablating a cornea with irradiation of an excimer laser beam, and to correct a refractive error of an eye. In this kind of apparatus, irradiation intensity distribution in an irradiation area of the laser beam (a cross-sectional area of the laser beam to be irradiated) and/or in an ablation area varies because of time-course change of an irradiation optical system or the like, and consequently, an ablation shape such as ablation depth distribution sometimes varies. Therefore, it is necessary to adjust the laser irradiation according to those variations.

In order to adjust the laser irradiation, the

applicant has proposed, in Japanese Patent Application
Unexamined Publication No. Hei6-226471 corresponding to
U.S. Patent No. 5,624,436, a method for forming a curved
surface on a transparent plate (PMMA plate) having a known
ablation rate by laser irradiation so as to have
predetermined refractive power, then measuring the
refractive power of the curved surface with a lens meter,
and calibrating data for ablation based on the
measurement result.

According to the above method, it has become possible
to easily adjust the laser irradiation in correspondence
with the variations in the irradiation intensity
distribution and the ablation shape; however, a further
technique for attaining more accurate ablation is
desired.

SUMMARY OF THE INVENTION

An object of the invention is to overcome the
problems described above and to provide a method and an
apparatus for obtaining irradiation intensity of a laser
beam, and an apparatus for irradiating the laser beam
that enable obtaining irradiation intensity
distribution of a laser beam easily, and attaining more
accurate ablation.

To achieve the objects and in accordance with the
purpose of the present invention, a method for obtaining
an irradiation intensity of a laser beam has the steps

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of inputting an intensity of fluorescence emitted from
a fluorescent glass, the fluorescence intensity being
obtained when the laser beam is irradiated onto the
fluorescent glass which emits the fluorescence by
irradiation of the laser beam with an ablation area of
a size required for processing an object to be processed,
and obtaining an irradiation intensity distribution of
the laser beam in the ablation area based on the inputted
fluorescence intensity.

In another aspect of the present invention, an
apparatus for obtaining an irradiation intensity of a
laser beam has input means for inputting an intensity
of fluorescence emitted from a fluorescent glass, the
fluorescence intensity being obtained when the laser beam
is irradiated onto the fluorescent glass which emits the
fluorescence by irradiation of the laser beam with an
ablation area of a size required for processing an object
to be processed, and obtaining means for obtaining an
irradiation intensity distribution of the laser beam in
the ablation area based on the inputted fluorescence
intensity.

Yet, in another aspect of the present invention, an
apparatus for irradiating the laser beam has irradiation
means having a laser source and an irradiation optical
system for irradiating a laser beam onto an object to
be processed, input means for inputting ablation data
for ablating the object to be processed into a

predetermined shape by irradiation of the laser beam, control means for obtaining control data for the irradiation means based on the inputted ablation data, a fluorescence detecting optical system having an area sensor, for obtaining an intensity of fluorescence emitted from a fluorescent glass, the fluorescence intensity being obtained when the laser beam is irradiated onto the fluorescent glass which emits the fluorescence by irradiation of the laser beam with an ablation area of a size required for processing the object to be processed, obtaining means for obtaining an irradiation intensity distribution of the laser beam in the ablation area based on the obtained fluorescence intensity, and calibrating means for calibrating at least one of the ablation data or the control data for the irradiation means based on the obtained irradiation intensity distribution.

Additional objects and advantages of the invention are set forth in the description which follows, are obvious from the description, or may be learned by practicing the invention. The objects and advantages of the invention may be realized and attained by the method and apparatus for obtaining irradiation intensity of a laser beam, and the laser beam irradiation apparatus in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

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The accompanying drawings, which are incorporated

in and constitute a part of this specification,

illustrate embodiments of the present invention and,

together with the description, serve to explain the

objects, advantages and principles of the invention. In

the drawings,

Fig. 1 is a view showing a schematic configuration

of an ophthalmic laser irradiation apparatus system

consistent with the present invention;

Fig. 2 is a view showing a schematic configuration

of an irradiation optical system and a control system

in a laser irradiation apparatus;

Fig. 3 is a view illustrating a typical shape of an

excimer laser beam;

Fig. 4 is a view showing a schematic configuration

of a dividing aperture plate and a dividing shutter;

Fig. 5 is a view illustrating synchronization

between initiation of image-capturing and oscillation

of a laser pulse;

Figs. 6A and 6B are views illustrating a summation

of images captured by a camera;

Figs. 7A to 7C are views illustrating a method for

calibrating data for ablation;

Fig. 8 is a view illustrating the method for

calibrating data for ablation represented in the form

of ablation depth; and

Fig. 9 is a view indicating a relationship between

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irradiation intensity of the laser beam and an ablation rate of a cornea.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A detailed description of one preferred embodiment of a method and an apparatus for obtaining irradiation intensity of a laser beam, and an apparatus for irradiating the laser beam embodied by the present invention is provided below with reference to the accompanying drawings. Fig. 1 is a view showing a schematic configuration of an ophthalmic laser irradiation apparatus system consistent with the present invention.

A laser beam irradiation apparatus 200 ablates a cornea of a patient's eye with an excimer laser beam. A laser light source and the like are integrated in a main body 201 of the irradiation apparatus 200. A laser beam from the laser light source is guided to an arm unit 202 and an end unit 204 attached to the end of the arm unit 202, and is irradiated onto the cornea of the patient's eye. Arranged inside of the main body 201 to the end unit 204 is an irradiation optical system to be described later. The end unit 204 is provided with a binocular microscope unit 203 for observing the patient's eye. The arm unit 202 is movable in horizontal directions (X and Y directions), and the end unit 204 is movable in a vertical direction (Z direction).

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Reference numeral 10 is a fluorescent glass used for measuring irradiation intensity distribution of the laser beam. The fluorescent glass 10 is comprised of a glass component such as SiO_2 or B_2O_3 and a rare-earth element such as Tb_2O_3 or Eu_2O_3, and emits visible fluorescence when it is irradiated with ultraviolet rays. A surface to be irradiated of the fluorescent glass 10 may be in a plate shape; however, it is preferably in a shape of a convex-curved surface having a curvature being approximate to that of a corneal shape of a human eye. For example, it is made to have a dome-shaped surface where a radius of curvature R = 7.8 mm which is an average radius of curvature of the human eye. A diameter of the dome-shaped surface is 12 mm, and it is preferably 10 mm or more. If the surface to be irradiated of the fluorescent glass 10 is formed into the shape of the convex-curved surface to resemble the cornea, the irradiation intensity distribution may be obtained while power loss due to influences of defocus of the laser beam and inclination of the surface to be irradiated at the time of actual corneal surgery is considered.

Reference numeral 11 is a holder for holding the fluorescent glass 10, and may be in any shape as long as it can stably hold the fluorescent glass 10. A housing of the holder 11 is preferably a shielded cylinder for reducing incidence of disturbance light. The fluorescent glass 10 is provided inside the shielded

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cylinder of the holder 11. Placed at the top of the shielded cylinder is an opening 10a for having the laser beam enter and passing the emitted fluorescence.

Fig. 2 is a view showing a schematic configuration of the irradiation optical system and a control system in the irradiation apparatus 200. The laser light source 210 emits an excimer laser beam with a wavelength of 193 nm. From the laser source 210, a laser beam of which a cross section is in a rectangular shape is generated and emitted as shown in Fig. 3. Intensity distribution in a horizontal direction of the emitted laser beam is approximately uniform, and intensity distribution in a vertical direction is the Gaussian distribution. The laser beam emitted from the laser source 210 is reflected by mirrors 211 and 212, and further reflected by a plane mirror 213. The mirror 213 is translatable (movable) in a direction of the arrow shown in Fig. 2 by a mirror driving unit 214, and translates (scans) the laser beam in the Gaussian distribution direction.

An image rotator 215 is rotatably driven about a central optical axis L by an image rotator driving unit 216, and rotates the laser beam about the optical axis L. Reference numeral 217 is a mirror.

Reference numeral 218 is a circular aperture having a circular opening for limiting an ablation area to a circular shape, and an aperture driving unit 219 changes an opening diameter thereof. Reference numeral 220 is

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a slit aperture having a slit opening for limiting the ablation area to a slit shape, and an aperture driving unit 221 changes opening width and direction. Mirrors 222 and 223 change a direction of the beam. A projecting lens 224 projects the openings of the circular aperture 218 and the slit aperture 220 onto the cornea Ec.

In addition, a dividing aperture plate 260 is disposed insertably and removably on an optical path between the slit aperture 220 and the mirror 222. The dividing aperture plate 260 further limits the ablation area (an irradiation area) in combination with a dividing shutter 265. The dividing aperture plate 260 and the dividing shutter 265 are used when an asymmetric component of the cornea Ec is ablated. When the dividing aperture plate 260 is viewed from the light source 210 side, six small circular apertures 261 of the same size are aligned as shown in Fig. 4. One or more shutter plates 266 of the dividing shutter 265 cover and uncover the small apertures 261 selectively, thereby enabling the ablation area (irradiation area) to be further limited to a small area for the laser irradiation. The dividing aperture plate 260 and the dividing shutter 265 are movable by a driving unit 268 within a plane vertical to the optical axis L.

A dichroic mirror 225 has a property of reflecting an excimer laser beam and transmitting visible light. The laser beam passed through the projecting lens 224

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is reflected by the dichroic mirror 225 and directed to and irradiated onto the cornea Ec. Placed above the dichroic mirror 225 are a fixation light 226, an objective lens 227, and the microscope unit 203.

A mirror 230 is disposed between binocular optical paths of the microscope unit 203 (on an optical axis of the objective lens 227). An image forming lens 231, a mirror 232, and a CCD camera 233 as an area sensor are disposed on an optical path at a reflecting side of the mirror 230. The camera 233 is connected to a computer 209. The objective lens 227, the mirror 230, the mirror 232, and the camera 233 constitute an optical system for detecting a luminance (intensity) of the fluorescence emitted from the fluorescent glass 10. The optical system may double as an image-pickup optical system for observing an anterior-segment of the patient's eye. The computer 209 is connected with an input unit 209a for inputting surgical data such as data on a pre-operative corneal shape and/or data on a correction amount, and with a monitor 209b. The computer 209 is provided with a memory 209c for storing image data from the camera 233, and performs processings such as calculation and calibration of data for ablation.

A control unit 250 controls the laser light source 210, each of the driving units and the like. The control unit 250 is connected with a foot switch 208, a controller 206 on which a variety of operation switches are disposed,

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and the computer 209.

Ablation performed by the laser irradiation apparatus 200 will be described hereinafter. In the case of the ablation with constant depth distribution, the mirror 213 is translated (moved) in the direction of the arrow shown in Fig. 2, and the laser beam in a rectangular shape is translated (scanned) in the Gaussian distribution direction at a rate based on a repetition frequency of a laser pulse from the laser source 210. The mirror 213 is moved in synchronization with the laser pulse. That is to say, after irradiating one pulse (or several pulses) at a certain travel position, the mirror 213 is moved to the next position, and after irradiating one pulse (or several pulses) , the mirror 213 is moved again. These operations are repeatedly provided from one end to the other end of the ablation area limited by the opening of the circular aperture 218. Then, every time the laser beam has been moved (scanned) in one direction, the movement (scanning) direction of the laser beam is changed by the rotation of the image rotator 215 at each predetermined angle to perform ablation within the opening of the circular aperture 218. Incidentally, as Japanese Patent Application Unexamined Publication No. Hei4-242644 corresponding to U.S. Patent No. 5,507,799 and Japanese Patent Application Unexamined Publication No. Hei6-114083 corresponding to U.S. Patent No. 5,637,109 describe a method for uniformly ablating

an object in detail, please refer to it for detail.

In myopic correction, when the ablation is performed deeply at a central part compared with a peripheral part so as to remove a spherical component which is rotationally symmetrical, the following procedure is performed. The laser beam is moved (scanned) in the Gaussian distribution direction within the opening of the circular aperture 218 by moving the mirror 213. Then, every time the laser beam has been moved (scanned) in one direction, the movement (scanning) direction of the laser beam is changed by the rotation of the image rotator 215 to perform ablation within the opening of the circular aperture 218. These processes are performed every time the opening diameter of the circular aperture 218 is sequentially changed. According to these processes, ablation may be performed on the spherical component which is deep at the central part of the cornea Ec and shallow at the peripheral part. In the case of removing a cylindrical component which is linearly symmetrical, the same control is provided using the slit aperture 220 instead of the circular aperture 218.

Further, in the case of partial ablation so as to remove an asymmetric component, the dividing aperture plate 260 is used. The dividing aperture plate 260 is disposed on the optical path of the laser beam to control positions of the small apertures 261 of the dividing aperture plate 260, and selectively open and close the

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small apertures 261 by driving the dividing shutter 265.
By the movement (scanning) of the laser beam caused by
the movement of the mirror 213, the laser beam of a small
area passing through the opening small apertures 261 is
partially irradiated onto the cornea Ec.

In the irradiation apparatus system as provided
above, a method for obtaining the irradiation intensity
distribution of the laser beam and adjusting the laser
irradiation will be described hereinafter. Firstly, the
fluorescent glass 10 is disposed at a predetermined
position with respect to the irradiation optical system
(the optical axis L) in the irradiation apparatus 200.
The switches on the controller 206 are operated to put
an operation mode of the apparatus into a calibration
mode for the irradiation intensity distribution, and the
foot switch 208 is pressed for the laser irradiation.
In the calibration mode, the opening diameter of the
circular aperture 218 is expanded so as to make the size
of the ablation area maximized as required for a corneal
surgery, and each of the driving units in the irradiation
optical system is controlled in the same manner as in
the case of the ablation of the object with the constant
depth distribution.

By the laser irradiation, the fluorescent glass 10
emits the fluorescence having the luminance
corresponding to the irradiation intensity of the laser
beam. The fluorescence emitted from the fluorescent

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glass 10 is photo-received by an image-pickup element of the camera 233. An output signal from the camera 233 is inputted to the computer 209, and a photo-received digital image having light intensity is stored in the memory 209c.

As previously mentioned, at the time of the ablation, the laser beam is moved (scanned) in the Gaussian distribution direction by the movement of the mirror 213. The laser beam is moved (scanned) in synchronization with the laser pulse, and the uniform ablation is attained by scanning the pulsed laser beam (see Japanese Patent Application Unexamined Publication No. Hei5-220189 corresponding to U.S. Patent No. 5,637,109). For example, the laser irradiation in one direction (one scan) in the ablation area limited by the opening of the circular aperture 218 is assumed to be attained with ten pulses. In the case of capturing a fluorescent image, an image capturing signal of the camera 233 is synchronized to a laser pulse oscillation signal as shown in Fig. 5. For example, when an oscillation frequency of the laser pulse is 50Hz, the capturing of one image by the camera 233 is also set at 50Hz, and initiation of the image capturing is synchronized to the timing of the laser pulse oscillation. Thus, the fluorescent image for every one pulse is captured by the camera 233. The image captured by the camera 233 is, as shown in Fig. 6A, stored in the memory 209c as an image having luminance

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distribution for each laser pulse. In addition, by
summing ten images.from the first pulse to the tenth pulse,
the luminance distribution in the ablation area limited
by the opening of the circular aperture 218 is obtained
as shown in Fig. 6B. That luminance distribution
represents the irradiation intensity distribution of the
laser beam at one scan.

Basically, the irradiation intensity distribution
in the objective ablation area may be obtained by one
scan; however, the irradiation apparatus 200 consistent
with the present embodiment changes the moving (scanning)
direction of the laser beam in a rectangular shape at
every angle of 60 degrees (six scans cover one lap).
Therefore, the irradiation intensity distribution
within the ablation area for one scan may be obtained
by irradiating the laser beam onto the fluorescent glass
10 for six scans with changing the moving (scanning)
direction, and then summing and averaging the luminance
distributions at each of the scans.

Besides, in the case of capturing the fluorescent
image, it is preferable to previously provide a
sensitivity correction to each pixel of the camera 233.
In addition, it is preferable to previously capture an
image before the laser irradiation is performed on the
fluorescent glass 10, and provide a differential
processing to it and the fluorescent image actually
captured by the laser irradiation. This precludes the

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influence of disturbance light and facilitates obtaining

only the luminance information of the fluorescence.

Further, at the time of capturing the fluorescent image,

unnecessary illumination such as illumination light for

observation is shut off. Incidentally, a positional

standard for the irradiation intensity distribution

obtained is determined based on an image-pickup position

of the camera 233.

When the irradiation intensity distribution of the

laser beam in the ablation area is obtained, the computer

209 employs it as fundamental data for adjusting the laser

irradiation. The irradiation apparatus 200 is provided

with an energy monitor for the purpose of energy

stabilization of the laser beam emitted from the laser

source 210, and is controlled by the control unit 250

so that a total energy amount per one pulse becomes

constant. The laser beam, however, is uneven in its

energy density at an irradiation position due to energy

loss produced inside the optical system before reaching

the irradiation position, and varies also over time.

Therefore, in the present embodiment, a relationship

between the energy density and an ablation rate is

previously stored, and the laser irradiation is adjusted

based on it. As for the relationship between the energy

density per one shot (one pulse) of the excimer laser

beam and the ablation depth per one shot (referred to

as the "ablation rate" in this description), it is

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confirmed that in a range of 100 to 400 mJ/cm², as the energy density increases, the ablation depth also increases almost linearly. Further, for the corneal surgery, the energy density of around 200 mJ/cm² is employed.

The relationship of the ablation rate (ablation depth/one shot) with the irradiation intensity of the laser beam may be obtained as follows. For example, when a beam having the energy density of 150 mJ/cm² at its central part is irradiated onto the PMMA plate, if the ablation depth of 30μ is obtained with 100 shots, the ablation rate in the case of the energy density being 150 mJ/cm² is 0.3μ. Likewise, by obtaining the ablation rates for different values of the energy density, a table which shows the relationship of the ablation rate with the energy density is obtained. Further, it is empirically confirmed that the ablation rate of the cornea is approximately twice as that of the PMMA plate. Accordingly, if a table of the relationship between the irradiation intensity of the laser beam and the ablation rate of the cornea (see Fig. 9) is stored in memory means of the computer 209, the ablation rate corresponding to the irradiation intensity is obtained. Further, if a three-dimensional ablation shape of the cornea being an object to be processed is divided by the ablation rate determined based on the irradiation intensity distribution of the laser beam, distribution of the

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number of shots (the number of scans in the present
apparatus) may be obtained. The laser irradiation may
be adjusted by reflecting the unevenness of the
irradiation intensity distribution as an increase or
decrease in the number of shots.

Here, the irradiation intensity distribution of the
laser beam at an arbitrary angle θ corresponding to a
certain meridian direction of the eye is assumed to be
obtained as data 300 shown in Fig. 7A for a profile of
the ablation rate. Then, the ablation rate at a position
P (r, θ) which is at the angle θ, and a distance r from
an irradiation center is assumed to be K(r, θ). The value
is utilized to calibrate the data for ablation. Assuming
that the data for ablation at the angle θ is inputted
as the ablation depth distribution data indicated as a
graph 301 in Fig. 7B and the ablation depth at the position
P (r, θ) is h, the number of shots S_h after the correction
is obtained by the following formula:

S_h = h/K(r, θ).

When it is calculated for the whole ablation area, it
is corrected to be distribution data on the number of
shots indicated as a graph 302 in Fig. 7C. Incidentally,
a graph 303 in Fig. 7C indicates distribution data on
the number of shots where the ablation rate K_0 at the
irradiation center is considered to be constant in the
whole ablation area.

In addition, the calibration of the data for ablation

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may be represented in a form of the ablation depth as follows, instead of being represented as the distribution data on the number of shots. If the ablation rate at the center at which the ablation rate is a maximum value in Fig. 7A is taken as K_0, a changing ratio of the ablation rate at the position P (r, θ) with respect to K_0 is K $(r, \theta) / K_0$. If the ablation depth at the position P (r, θ) is h as with Fig. 7B, the ablation depth h' after the correction is obtained by the following formula:

h' = h/(K (r, θ) / K_0).

When it is calculated for the whole ablation area, it is corrected to be the ablation depth distribution data indicated as a graph 304 in Fig. 8.

Besides, the data for ablation is obtained by obtaining the post-operative corneal shape where a lens component corresponding to an objective correction amount (a correction amount for correcting SPH, CYL, or Axis being subjective values or objective values, or a correction amount for correcting aberration of the eye) is removed from the pre-operative corneal shape previously measured, and by calculating a difference between the pre-operative and post-operative corneal shapes. The data for ablation is obtained by the computer 209 based on the pre-operative corneal shape inputted by the input unit 209a and the objective correction amount; however, the data calculated by another analyzer may be inputted to the computer 209.

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Based on the distribution data on the number of shots
after the correction (or the distribution data on the
ablation depth after the correction), the computer 209
calibrates driving information for each of the driving
units 214, 216, 219, 221, 268, and the like that change
the position of the irradiation area and the ablation
area. The distribution data on the number of shots (or
the distribution data on the ablation depth) are divided
into the rotationally symmetric component represented
by the spherical component, the linearly symmetric
component represented by the cylindrical component, and
the asymmetric component other than those components.
As for the rotationally symmetric component, the opening
diameter of the circular aperture 218 per one scan is
obtained. Similarly, as for the linearly symmetric
component, the opening width of the slit aperture 220
per one scan is obtained. As for the asymmetric
component, the travel position of the dividing aperture
plate 260 and the closing and opening of the dividing
shutter 265 per one scan are obtained. At the time of
the actual ablation, each driving unit is controlled by
the control unit 250 based on control data being a result
of calculation by the computer 209.

Incidentally, as for the ablation of the
rotationally symmetric component or the linear symmetric
component, instead of controlling the circular aperture
218 or the slit aperture 220, the movement of the laser

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beam of which the cross section is in a rectangular shape,
and the number of shots at each irradiation position may
be controlled as described in U.S. Patent 5,800,424
corresponding to Japanese Patent Unexamined
Publications Nos. Hei8-66420 and Hei9-122167. Besides,
needless to say, the number of shots may be treated as
irradiation time of the laser beam. The number of shots
or the irradiation time may be controlled by controlling
the laser source 210.

The above-described laser irradiation apparatus has
a constitution where the position of the irradiation area
and the ablation area are changed by the translational
scan of the laser beam and the control of the aperture
218 and the like. However, it may be an apparatus of such
type that changes a spot position (position of the
irradiation area) of the laser beam by an optical system
which scans the laser beam formed into a small spot of
about 0.1 to 1 mm (it may be constituted by two
galvano-mirrors or the like) in the X and Y directions.
Also in this type of apparatus, in the calibration mode,
the laser beam is scanned so as to ablate with the constant
depth distribution within the ablation area required for
a corneal surgery, and the image on the camera 233 is
captured in synchronization with the laser pulse
oscillation signal. Then, the captured images are
summed, so that the irradiation intensity distribution
of the laser beam in one scan (one plane) of the ablation

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area is obtained. The laser irradiation may be adjusted by correcting the data for ablation or correcting the distribution data on the number of shots (irradiation time) at each irradiation position as previously described based on a change in the ablation rate distribution obtained by the irradiation intensity distribution. Further, in an apparatus of such type that irradiates a laser beam in a large spot, the laser irradiation may be adjusted by correcting the data for ablation or controlling the ablation area (irradiation area) as previously described.

As described above, according to the present invention, the irradiation intensity distribution of the laser beam is easily obtained and more accurate ablation may be performed.

The foregoing description of the preferred embodiments of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and modifications and variations are possible in the light of the above teachings or may be acquired from practice of the invention. The embodiments chosen and described in order to explain the principles of the invention and its practical application to enable one skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular

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use contemplated. It is intended that the scope of the
invention be defined by the claims appended hereto, and
their equivalents.